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Repeatability and Reproducibility of Oblique Moving Deformable Barrier Test Procedure

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Abstract

National Highway Traffic Safety Administration (NHTSA) has developed an Oblique Offset Moving Deformable Barrier test procedure. For this test procedure to be viable, it must be repeatable within each test facility and it must be reproducible between test facilities. Three tests of a single vehicle model were conducted at three different test facilities, a total of nine tests, to evaluate repeatability and reproducibility. The responses of the vehicle and its occupants were evaluated using three different methodologies to quantify the repeatability within a single test facility and reproducibility among the three test facilities. The first two methods evaluated the time-history of the measured data and the third method only used the peak values. Overall, this test series demonstrated repeatable and reproducible results for the OMDB, vehicle, and driver occupant in the oblique offset test procedure. The method using only the peak values indicates more variability. This study has also identified a few areas where the test procedure can be refined, including improved vehicle sensor mounting requirements and dummy seating procedure.

Introduction

There are many variables that affect the response of an anthropomorphic test device (ATD) in an Offset Moving Deformable Barrier (OMDB)-to-vehicle crash test. These test parameters cannot be completely controlled, but the variability can be minimized by a thorough test procedure. In addition to the parameters that affect the repeatability and reproducibility (R&R) of the ATD, other parameters affect the R&R of the test, including: 1) test variation such as the actual overlap and impact velocity; 2) performance and specifications of the OMDB; 3) variations in the manufacture of the vehicle; 4) vehicle response, such as weld strength; and 5) ATD initial position. The extent to which each of these parameters or combination of these parameters contribute to the overall R&R of the oblique test and the ATD injury assessment is not known.

In a computational study, Peddi et al. [1] demonstrated the effects of two vehicle parameters on test repeatability by performing simulations of a collinear impact of a mid-size SUV into a compact vehicle. The baseline overlap of the SUV was 50% of the compact vehicle. First, Peddi et al. [1] investigated the effects of overlap by moving the lateral impact point 40 mm to investigate the effect on peak Gs of the compact vehicle. The peak Gs of the compact vehicle changed by 11% with this change in overlap. Peddi et al. [1] investigated the effects of one manufacturing variability parameter by changing the stiffness of the compact vehicle by 10 percent. The peak Gs of the compact vehicle changed by 6 percent with this change in stiffness.

The severity of the vehicle structural response in the oblique crash test should be considered for the assessment of R&R to be meaningful. For example, if the intrusion is too severe, the ATD response will be dominated by the high intrusion levels such that the other sources of variability within the test procedure are overshadowed and cannot be assessed. From a previously-published set of left and right OMDB tests (Saunders et al., [2]), the 2014 Mazda CX-5 demonstrated one of the lowest intrusion and occupant injury risk, while exhibiting well-controlled occupant kinematics. Assuming that the performance of the 2014 model year vehicle would be similar to the 2016 model year vehicle available at the time of the present study, NHTSA selected the Mazda CX-5 as the target vehicle for R&R evaluation of the OMDB test procedure.

To assess the test repeatability (within a single test facility) and the test reproducibility (between different test facilities), the oblique test procedure was used to perform testing at three different laboratories. At each laboratory, oblique crash tests were performed on three 2016 Mazda CX-5 vehicles. Each CX-5 had the same trim level and was manufactured in the same month to try to minimize any potential variation in manufacturing. During this test series, several of the 2016 CX-5 vehicles experienced significant breakage of the windshield glazing resulting in fabric tears in the passenger airbags. These sporadic tears caused loss of pressure in the airbag and large variations in the right passenger kinematics and injury measures. Therefore, analysis was performed on the driver only.

This paper evaluates three different methods for determining repeatability and reproducibility. The first and second methods evaluate the time-histories, whereas the third method only used peaks.

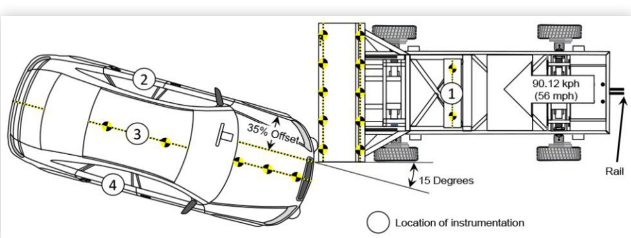
Test Setup

Figure 1 shows the general test setup and the location of the instrumentation for the OMDB crash test. The OMDB impacts the target vehicle at a test speed of 90km/h at a 15-degree offset and at 35% overlap of the target vehicles' overall width (excluding mirrors and door handles). The outer edge of the OMDB is aligned with the overlap mark on the target vehicle. Two Test Device for Human Occupant Restraint 50th percentile male (THOR-50M) ATDs, as defined by the September 2015 drawing package [3] and qualification specifications [4], were positioned in the driver and the right front passenger seats. In all nine crash tests, THOR serial number DO9798 was positioned in the driver's seat, and THOR serial number DL9207 was positioned in the right front passenger's seat. Qualification tests were conducted before and after each set of three crash tests. The test procedure requires documentation of several pre-and post-test measurements including: 1) OMDB test weight; 2) OMDB center of gravity (CG) location aft of front axle, 3) OMDB impact velocity; 4) struck vehicle weight; 5) vehicle CG location aft of front axle, 6) overlap distance between OMDB and struck vehicle and the height of the OMDB at impact. The oblique test procedure provides more detailed description on the test setup [5].

Accelerometers were used to measure acceleration and calculate velocity for both the OMDB and the test vehicle (Figure 1). Angular rate sensors were also used to measure angular velocity and calculate rotation. The OMDB was instrumented with a 6-axis cube at the center of gravity (OMDB CG, location 1). The 6-axis cube measured the x, y, and z acceleration components and the angular rate components of the OMDB. The vehicle was instrumented with a 3-axis accelerometer at the left and right rear sill (locations 2 and 4, respectively) and a 6-axis cube behind the center console (VEHCG, location 3). Table 1 shows the naming convention used throughout the paper for the test vehicle and the OMDB time histories.

The THOR-50M occupants were instrumented to record the critical measurements that are described in the OMDB test procedure. The present study focuses on the measurements used to evaluate risk of injury (Table 2), as described

FIGURE 1 General test setup for oblique test procedure and location of instrumentation



in Saunders et al [2]. Table 2 also shows the naming convention for dummy time-histories used throughout the paper.

Table 3 shows the naming convention for each test used throughout this report. The table also includes the test number in the NHTSA crash test database [6], from which photos, videos, reports, and time-history data can be obtained.

Methodology

Three different methodologies were evaluated for determining repeatability and reproducibility of the OMDB test procedure.

TABLE 1 Naming convention for test vehicle and OMDB time-histories

Name	Description
VehLRaccRes	Test vehicle left rear sill resultant acceleration (x,y)
VehLRvelRes	Test vehicle left rear sill resultant velocity (x,y)
VehRRaccRes	Test vehicle right rear sill resultant acceleration (x,y)
VehRRvelRes	Test vehicle right rear sill resultant velocity (x,y)
VehCGav	Test vehicle CG angular velocity (z)
VehCGang	Test vehicle CG rotation (z)
OMDBaccRes	OMDB CG resultant acceleration (x,y)
OMDBvelRes	OMDB CG sill resultant velocity (x,y)
OMDBCGav	OMDB CG angular velocity (z)
OMDBCGang	OMDB CG rotation (z)

TABLE 2 Naming convention for dummy time-histories

Name	Description
HeadACRes	Head CG resultant acceleration
HeadAVx	Head CG angular velocity (x)
HeadAVy	Head CG angular velocity (y)
HeadAVz	Head CG angular velocity (z)
NeckFz	Upper neck force (z)
NeckMy	Upper neck moment (y)
ChestLL	Resultant left lower chest displacement
ChestRL	Resultant right lower chest displacement
ChestLU	Resultant left upper chest displacement
ChestRU	Resultant right upper chest displacement
AcetabRIRes	Resultant right acetabular force
AcetabLERes	Resultant left acetabular force
FemurLE	Left femur force (z)
FemurRI	Right femur force (z)
TibiaRUFz	Right upper tibia force (z)
TibiaRUMomRes	Right upper tibia moment resultant (x,y)
TibiaRLFz	Right lower tibia force (z)
TibiaRLMomRes	Right lower tibia moment resultant (x,y)
TibiaLUFz	Left upper tibia force (z)
TibiaLUMomRes	Left upper tibia moment resultant (x,y)
TibiaLLFz	Left lower tibia force (z)
TibiaLLMomRes	Left lower tibia moment resultant (x,y)

TABLE 3 Test names and NHTSA test numbers

Lab	Test Number	Combined Name	NHTSA VEHDB Test Number [6]
Lab1	1	Lab1_1	9499
	2	Lab1_2	9500
	3	Lab1_3	9501
Lab2	1	Lab2_1	9699
	2	Lab2_2	9725
	3	Lab2_3	9726
Lab3	1	Lab3_1	9802
	2	Lab3_2	9806
	3	Lab3_3	9807

The first two methods evaluate the similarity between two time-histories, whereas the third method only uses peaks to determine R&R.

CORA

CORrelation and Analysis (CORAplus) [7] provides a methodology to objectively compare the time histories of the measurements and quantify how two or more signals compare on a scale of 0 to 1, where a score of 1 indicates that the signals are identical. CORA software uses two methods to evaluate the correlation two or more signals. The corridor method compares the deviation between curves while the cross correlation method compares curve characteristics such as shape, phase shift, and size. A higher total CORA score represents a higher correlation between each test or measurement.

ISO 18571

The ISO 18571 method is similar to the CORA method. The ISO method uses the corridor method and a cross-correlation rating consisting of phase, magnitude, and slope. The differences in the calculations can be found in the CORAplus manual. The ISO method categorizes the overall ISO score into the following four ranges (Table 4). The ISO method only allows comparison of two time-histories.

Coefficient of Variation

Coefficient of variation (CV) is calculated (Eqn. 1) by dividing the standard deviation (Eqn. 2) by the mean (Eqn. 3) of the given measurement values for each test in the group. The sample standard deviation is used here since only the values in each group are being considered, not a projection on a greater population. Lower CV values represent more repeatable test procedures.

$$CV = \frac{\sigma}{\mu} \times 100\% \tag{1}$$

$$\sigma = \sqrt{\frac{\Sigma(x-\mu)^2}{n-1}} \tag{2}$$

$$\mu = \frac{1}{n}\Sigma x \tag{3}$$

TABLE 4 Division of the ISO rating

Grade	Rating R
Excellent	R>0.94
Good	0.80<R<=0.94
Fair	0.58<R<=0.80
Poor	R<=0.58

Rhule et al. [8] rated the ATD R&R response as "poor" when CV greater than 10 percent. In NHTSA's proposed rulemaking [9] for the Q3 rated different ranges for "poor" R&R. The CV range used for "poor" R&R was greater than 10 percent for repeatability and greater than 15 percent for reproducibility. The ATD qualification tests are very controlled laboratory procedures. The ATD R&R is just one of the components that affect the R&R of the oblique crash test procedure. NHTSA did not quantify R&R in its upgrade to the test procedure for Federal Motor Vehicle Standard No.214, "side impact protection" [10]. In this evaluation some of the CVs were between 15 and 20 percent. Also, Saunders and Parent [11] demonstrated the oblique test procedure repeatability was as repeatable as the current full frontal and offset deformable barrier test procedure. In the same study, Saunders and Parent [11] used a CV of less than or equal to 20 percent to determine if the oblique test procedure repeatability is acceptable

Generally, CV is presented as a percentage. However, the CV was reformulated for the purposes of this study to facilitate comparison with the CORA and ISO methods. The modified CV (CVmod) was calculated by converting the CV back to a ratio and subtracting from 1 (Eqn. 4), resulting in a value between 0 and 1, with 1 indicating perfect agreement. For example, a CV of 10% would be equivalent to a CVmod of 0.90.

$$CV_{\text{mod}} = 1 - \frac{CV}{100\%} = 1 - \frac{\sigma}{\mu} \tag{4}$$

Grade Ranges

As shown in Table 4, a relationship between the numeric rating and classification for the ISO method. A relationship has also been defined for CV as it applies to ATD qualification tests [8] [9]. However, such relationships have not been defined for CORA, CVmod, or the general application of these methods to the assessment of vehicle crash test procedures R&R. To demonstrate the R&R of the OMDB test procedure, a grading system was defined to relate the numeric rating for each of the three methods in this study to a simple three-tiered classification: good, fair, and poor (Table 5). This grading system has the same boundaries as the ISO method (Table 4), except that "excellent" and "good" ranges were combined into a "good" range. The CVmod was divided into only two categories, good and poor. Good for CV was defined as a CV greater than or equal to 0.80.

CORA and ISO CALCULATION

To calculate the CORA and ISO scores the CORA-Plus [7] software was used. For this analysis the CORA and ISO examples provided when downloading the CORA-Plus [7] were used. The only thing modified in these files was the

TABLE 5 Classification of calculated scores for CORA, ISO, and CVmod.

Grade	Calculated Score ISO, CORA	Calculated Score CV_{mod}
Good	R>0.80	R>=0.80
Fair	0.58<R<=0.80	N/A
Poor	R<=0.58	R<0.80

TABLE 6 Nomenclature for comparisons

Name	Description
Lab1	Comparison of the three tests for Lab1
Lab2	Comparison of the three tests for Lab2
Lab3	Comparison of the three tests for Lab3
LabAll	Comparison of all nine tests

reference to the time-history data and the time range for evaluation. As specified in the manual all data was sampled at 0.1 ms. The CORA and ISO methods are generally used to compare a simulation result to test results. However, in this analysis all of the data were from experimental results and therefore it is unknown which test should be considered as the simulation time-history and which time histories should be used to calculate the average. As noted above, the ISO grade listed above is only valid when comparing two signals. Therefore, for this analysis each time-history was compared to every other time-history individually. For example, for Lab1, Lab1_1 is compared to Lab1_2, then Lab1_1 is compared to Lab1_3, and finally Lab1_2 is compared to Lab1_3. After the CORA scores are calculated for each test relative to each other test, the average of all the CORA scores is used as the final score for this set of time-histories. LabAll compares all time-history from all nine tests to each other. In all LabAll will have a total of thirty-six comparisons. Table 6 shows the nomenclature for each comparisons.

For CORA and ISO the curves should only be evaluated during the main event of the time-histories. Figure 2 (a) and (b) shows that the acceleration and angular velocity of the vehicle is over by 100 ms. Figure 3 shows the head angular velocity main event is between 150 to 200 ms. Therefore, for this analysis the CORA and ISO scores were calculated using the time range from 0 to 100 ms for the vehicle and OMDB parameters. For the dummy the time range used was from 0 to 200ms.

Results

Input Parameters

The first part of R&R is to ensure the input parameters are consistent. Table 7 shows the initial parameters of the OMDB and the vehicle. The OMDB test weights were similar between tests, but the location of the OMDB CG aft of the front axle has a maximum difference between tests of 84 mm. Also, the test weights for the vehicle were similar, but the location of the CG aft of the front axle has a maximum difference between tests of 61 mm. The impact velocities of the OMDB were similar. All initial parameters demonstrated excellent repeatability based on CVmod.

Figure 4 shows the impact point for all 9 tests. The graph is plotted such that points are as viewed when looking at the front of the vehicle. Therefore, if Distance Y is positive, the

FIGURE 2 Example of the time of the main event of the vehicle

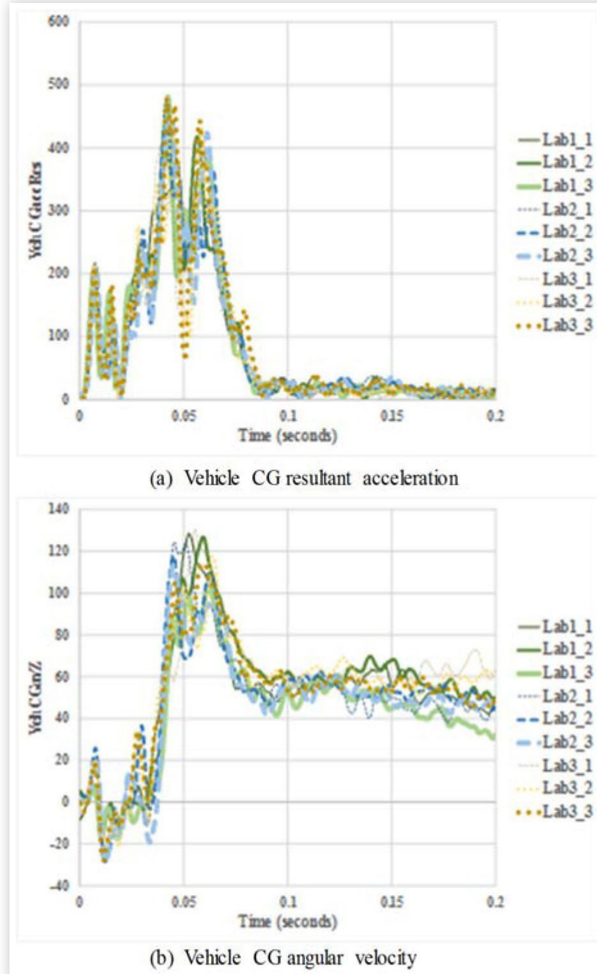


FIGURE 3 Example of the time of the driver

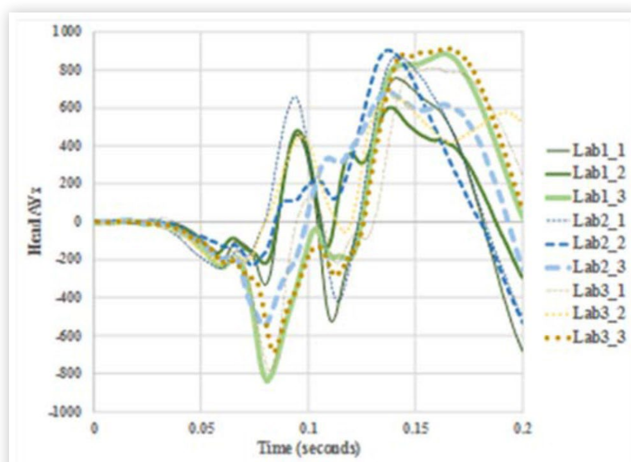
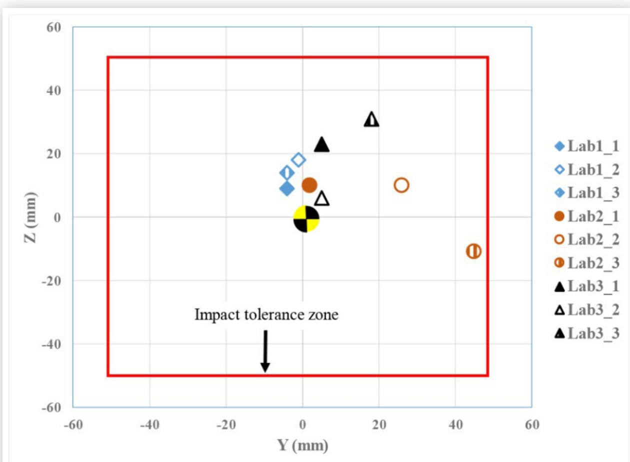


TABLE 7 Initial parameters of the OMDB and the vehicle

Test Name	OMDB Weight (kg)	OMDB CG (mm)	Vehicle Weight (kg)	Vehicle CG (mm)	Impact Velocity (km/h)
Lab1_1	2491	904	1775	1202	90.07
Lab1_2	2491	904	1775	1194	90.08
Lab1_3	2491	904	1772	1193	90.1
Lab2_1	2497	988	1788	1254	90.65
Lab2_2	2497	988	1791	1252	89.75
Lab2_3	2497	988	1790	1224	89.74
Lab3_1	2499	977	1790	1225	90.27
Lab3_2	2498	977	1798	1214	90.19
Lab3_3	2498	977	1799	1227	90.23
Avg.	2495	956	1786	1221	90.12
Std Dev.	3.2	37.3	9.5	21.2	0.260
CV (%)	0.1	3.9	0.5	1.7	0.3

FIGURE 4 Actual impact point from desired impact point



overlap is less than 35 percent, and if the Distance Z is positive, the OMDB impacted the target vehicle above the desired impact point. All 9 tests were inside the specified tolerance of +/- 50 mm in both the y and z-axis. Three of the nine tests stand out when compared to the other tests. Lab2_2 and Lab2_3 were the furthest from the desired target point in the Y direction. Lab3_3 was the furthest from the desired target point in the Z direction.

OMDB Response

The second part of R&R is determining the repeatability and reproducibility of the measured OMDB responses. Table 8 shows the CORA scores for all three labs and LabAll of the OMDB parameters. The CORA scores for all three labs and LabAll was rated good, except for OMDBaccRes for Lab2 and OMDBaccRes for LabAll. The OMDBaccRes was rated "fair" for Lab2 and LabAll. Note, ND means the data collected was questionable.

Figure 5 shows an overlay of the OMDBaccRes for all the tests at the 9 labs. Even with the data filtered at CFC60 Lab 2 data exhibits more noise in the acceleration curves due to vibration of the mounting plate. This was due to the placement of the accelerometers being placed on a non-ruggedized structure. It was determined post test series that the accelerometer plate needed to be on a frame rail to reduce the vibration. If Lab2's data is over filtered (CFC30) to remove the noise in the data, the CORA score for Lab2 OMDBaccRes went from 0.70 to 0.98 and LabAll went from 0.79 to 0.96.

Table 9 shows the ISO scores for all three labs and LabAll of the OMDB parameters. The ISO method rated the OMDB similar to CORA except for the OMDBav. ISO gave OMDBCGav a fair rating for Lab2, Lab3 and LabAll. Looking at the ISO scores when Lab2 is over filtered, the OMDBaccRes goes from 0.67 to 0.92 for Lab2 and LabAll goes from 0.73 to 0.82 for OMDBaccRes.

Table 10 shows the CVmod scores for all three labs and LabAll of the OMDB parameters. Here CVmod indicated

TABLE 8 CORA OMDB scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
OMDBaccRes	0.97	0.70	0.98	0.79
OMDBvelRes	1.00	0.97	1.00	0.95
OMDBav	ND	0.88	0.81	0.84
OMDBang	ND	0.94	0.96	0.94

FIGURE 5 OMDBaccRes for all labs filtered at 60 CFC

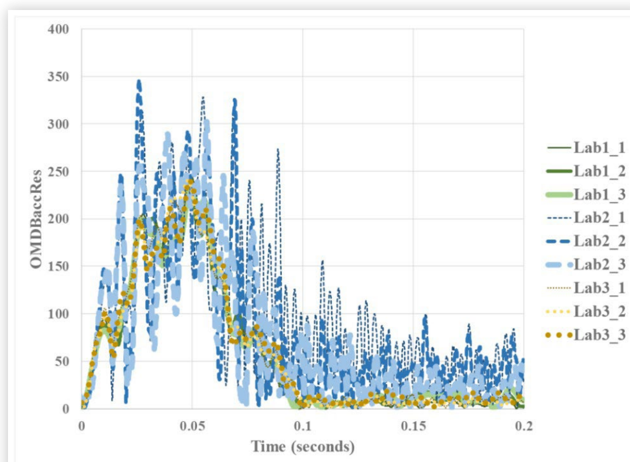


TABLE 9 ISO OMDB scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
OMDBaccRes	0.92	0.67	0.92	0.73
OMDBvelRes	0.98	0.92	0.98	0.91
OMDBav	ND	0.76	0.72	0.74
OMDBang	ND	0.93	0.94	0.93

TABLE 10 CVmod OMDB scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
OMDBaccRes	0.97	0.93	0.99	0.83
OMDBvelRes	0.99	0.88	0.98	0.79
OMDBav	ND	0.95	0.74	0.77
OMDBang	ND	0.96	0.97	0.94

"poor" rating for LabAll for OMDBvelRes. CVmod also indicated "poor" results for OMDBCGav for Lab3 and LabAll. Again if Lab2 data is over filtered the OMDBvelRes for LabAll goes 0.79 to 0.98.

Figure 6 shows OMDBavZ for test 3 of Lab3 (Lab3_3) and departs from Lab3 test 1 and test 2 after 20 ms. Then test 3 of Lab3 similar to test 1 and test 2 of Lab3 after 54 ms.

Vehicle Response

The third part of R&R is determining the repeatability and reproducibility of the measured vehicle responses. Table 11, Table 12, and Table 13 show the CORA, ISO, and CVmod scores for the test vehicle parameters, respectively. It is shown for all three tables that all the scores are in the "good" range except for the ISO score for the VehCGav for Lab1 and LabAll, and the CVmod score for VehRRaccRes for Lab3 (rated "poor"). The "poor" rating for CV of VehRRaccRes for Lab3 was due to a spike in the data around 16 ms. If the spike is removed the CV changes from 0.71 to 0.94.

FIGURE 6 OMDBavZ for Lab3

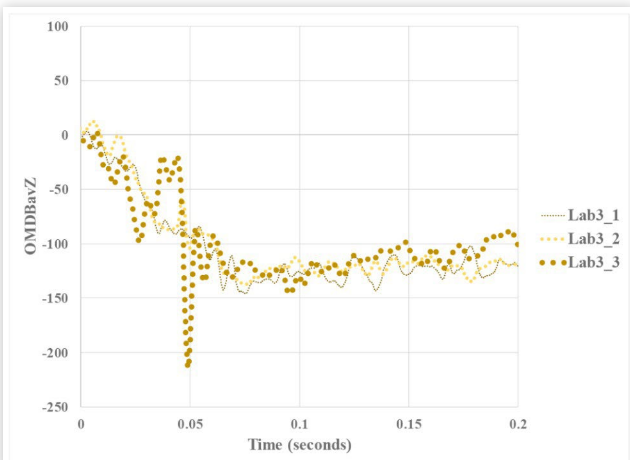


TABLE 11 Test vehicle CORA scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
VehLRaccRes	0.94	0.93	0.94	0.92
VehLRvelRes	1.00	0.99	0.99	0.99
VehRRaccRes	0.96	0.97	0.95	0.94
VehRRvelRes	1.00	1.00	0.87	0.95
VehCGav	0.87	0.90	0.90	0.85
VehCGang	0.90	0.92	0.98	0.94

TABLE 12 Test vehicle ISO scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
VehLRaccRes	0.89	0.88	0.89	0.86
VehLRvelRes	0.98	0.97	0.96	0.97
VehRRaccRes	0.91	0.91	0.90	0.88
VehRRvelRes	0.98	0.98	0.87	0.94
VehCGav	0.80	0.86	0.84	0.79
VehCGang	0.90	0.92	0.97	0.93

THOR Driver Upper Body Response

The fourth part of R&R is determining the repeatability and reproducibility of the measured ATD's responses. Table 14 shows the CORA scores for the THOR upper body parameters. CORA showed a "good" score for all three Labs and LabAll for HeadACRes, NeckFz, and ChestRU. For HeadAVy and ChestRL, Lab3 showed a "fair" CORA score while the rest showed "good", and for ChestLU, each lab was rated "good" but the across-lab comparison was rated "fair". HeadAVx, NeckMy, and ChestLL were rated "fair for all available comparisons except HeadAVx at Lab3 ("poor"). HeadAVz was rated "poor" for all comparisons except for Lab3, where it was rated to be "fair". The classifications based on CORA were the same in three-out-of-four or all four of the comparisons for each upper body metric.

THOR upper body parameter classifications based on the ISO score were less consistent than those based on the CORA score (Table 15). Four of the parameters received the same classification for all comparisons: two rated "good" (NeckFz and ChestRU), one rated "fair" (NeckMy), and one rated "poor" (ChestLL). All other upper body parameters were rated inconsistently; the largest variation was for ChestRL, which was classified as "good" by Lab1 and Lab2, "poor" by Lab3, and "fair" overall.

TABLE 13 Test vehicle CVmod scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
VehLRaccRes	0.92	0.93	0.96	0.91
VehLRvelRes	1.00	0.97	0.98	0.97
VehRRaccRes	0.99	0.92	0.71	0.81
VehRRvelRes	0.98	0.99	0.95	0.96
VehCGav	0.88	0.95	0.93	0.93
VehCGang	0.89	0.96	0.96	0.92

TABLE 14 THOR upper body CORA scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
HeadACRes	0.94	0.95	0.87	0.90
HeadAVx	0.67	0.80	0.53	0.67
HeadAVy	0.87	0.91	0.77	0.82
HeadAVz	0.53	0.58	0.60	0.57
NeckFz	0.91	0.91	0.88	0.89
NeckMy	0.63	0.79	0.62	0.62
ChestLL	ND	0.69	0.61	0.65
Chest RL	0.90	0.94	0.60	0.82
ChestLU	0.88	0.89	0.84	0.76
ChestRU	0.99	0.98	0.90	0.93

TABLE 15 THOR upper body ISO scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
HeadACRes	0.94	0.85	0.79	0.81
HeadAVx	0.67	0.77	0.51	0.67
HeadAVy	0.85	0.88	0.75	0.81
HeadAVz	0.58	0.59	0.58	0.59
NeckFz	0.84	0.84	0.84	0.83
NeckMy	0.68	0.78	0.65	0.65
ChestLL	ND	0.57	0.47	0.53
Chest RL	0.88	0.90	0.47	0.78
ChestLU	0.83	0.80	0.76	0.68
ChestRU	0.95	0.93	0.85	0.89

TABLE 16 THOR upper body CVmod scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
HeadACRes	0.87	0.86	0.99	0.86
HeadAVx	0.76	0.79	0.62	0.75
HeadAVy	0.91	0.96	0.95	0.93
HeadAVz	0.81	0.86	0.84	0.85
NeckFz	0.91	0.90	0.93	0.92
NeckMy	0.83	0.84	0.78	0.82
ChestLL	ND	0.78	0.61	0.71
Chest RL	0.95	0.93	0.74	0.86
ChestLU	0.88	0.91	0.95	0.89
ChestRU	0.99	0.95	0.97	0.93

Table 16 shows the CVmod scores for the THOR upper body parameters. CVmod shows more consistent classifications than ISO or CORA, with disparate ratings for only two of the ten parameters. All parameters except for HeadAVx, NeckMy, ChestLL, and ChestRL are rated "good" across the board. HeadAVx and ChestLL are rated "poor" for all available comparisons. NeckMy and ChestRL are rated "poor" by Lab3, but "good" for all other comparisons.

THOR Driver Lower Body Response

All classifications based on CORA scores for the THOR lower body parameters were "fair" or "good" (Table 17). All parameters were classified as "good" except for FemurRI, TibiaRUFz, TibiaRUMomRes, and TibiaRLFz, which were rated "fair" by at least one lab, and TibiaRLMomRes, which was rated "fair" across the board.

Similar to the CORA-based classifications, the classifications based on ISO scores were all "fair" or "good" for the THOR lower body parameters (Table 18), though generally the ISO scores were lower and there were more "fair" ratings than "good" ratings. The ISO scores did follow a similar trend to the CORA scores, with the FemurLE and TibiaLLFz receiving the highest scores and consistently "good" ratings, and the TibiaRUMomRes and TibiaRLMomRes receiving the lowest scores and correspondingly "fair" ratings.

TABLE 17 THOR lower body CORA scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
AcetabRIRes	0.88	0.87	0.83	0.86
AcetabLERes	0.92	0.86	0.86	0.85
FemurLE	0.95	0.92	0.90	0.87
FemurRI	0.91	0.83	0.75	0.79
TibiaRUFz	0.85	0.84	0.75	0.77
TibiaRUMomRes	0.65	0.82	0.69	0.68
TibiaRLFz	0.92	0.88	0.83	0.84
TibiaRLMomRes	0.79	0.80	0.73	0.73
TibiaLUFz	0.91	0.81	0.83	0.82
TibiaLUMomRes	0.83	0.88	0.80	0.82
TibiaLLFz	0.95	0.91	0.93	0.91
TibiaLLMomRes	0.88	ND	0.87	0.87

TABLE 18 THOR lower body ISO scores within each Lab and LabAll

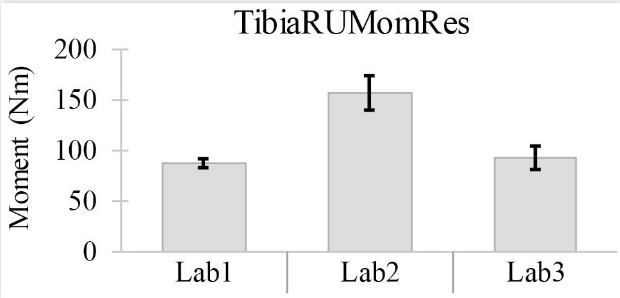
	Lab1	Lab2	Lab3	LabAll
AcetabRIRes	0.81	0.81	0.76	0.80
AcetabLERes	0.86	0.80	0.82	0.80
FemurLE	0.89	0.86	0.83	0.83
FemurRI	0.84	0.81	0.75	0.77
TibiaRUFz	0.81	0.79	0.72	0.74
TibiaRUMomRes	0.60	0.77	0.64	0.62
TibiaRLFz	0.84	0.83	0.78	0.79
TibiaRLMomRes	0.76	0.79	0.71	0.69
TibiaLUFz	0.82	0.76	0.77	0.77
TibiaLUMomRes	0.76	0.82	0.72	0.76
TibiaLLFz	0.88	0.84	0.85	0.85
TibiaLLMomRes	0.82	ND	0.80	0.81

TABLE 19 THOR lower body CVmod scores within each Lab and LabAll

	Lab1	Lab2	Lab3	LabAll
AcetabRIRes	0.89	0.86	0.89	0.89
AcetabLERes	0.89	0.97	0.86	0.89
FemurLE	0.86	0.95	0.95	0.87
FemurRI	0.91	0.80	0.85	0.86
TibiaRUFz	0.97	0.83	0.67	0.79
TibiaRUMomRes	0.95	0.89	0.88	0.69
TibiaRLFz	0.90	0.76	0.78	0.81
TibiaRLMomRes	0.88	0.82	0.79	0.64
TibiaLUFz	0.89	0.79	0.90	0.85
TibiaRLUMomRes	0.83	0.85	0.87	0.86
TibiaLLFz	0.96	0.81	0.90	0.89
TibiaLLMomRes	0.82	ND	0.92	0.87

CVmod scores for the THOR lower body parameters show at least two "good" classifications for each parameter, with about half of the parameters classified as "good" for all comparisons (Table 19). "Poor" classifications occurred in two parameters at Lab2 (TibiaRLFz and TibiaLUFz), three

FIGURE 7 Mean and standard deviation for the TibiaRUMomRes parameter values for each lab.



parameters at Lab3 (TibiaRUFz, TibiaRLFz, and TibiaRLMomRes), and three parameters across all labs (TibiaRUFz, TibiaRUMomRes, and TibiaRLMomRes). Ratings based on CVmod for the lower body parameters are directionally consistent with those based on CORA scores, as all but TibiaRUFz, TibiaRUMomRes, and TibiaRLMomRes were rated "good" by both metrics.

The R&R classification of the TibiaRUMomRes parameter by CVmod highlights the difference between repeatability and reproducibility. While repeatability is rated "good" at each of the three labs, the reproducibility (calculated for all labs) is rated "poor". This occurs because the measurements were inconsistently consistent; while the standard deviations at each lab were relatively small, the means were quite different (Figure 7). Specifically, the mean value for Lab2 is notably higher than that of Lab1 and Lab3.

Discussion

This study evaluated the repeatability and reproducibility of the OMDB test procedure by comparing barrier, vehicle, and occupant responses from three tests at each of three test labs. One limitation of this study is that this sample size was limited by cost and schedule requirements, and as such the power was not sufficient to reach statistically-significant conclusions at a meaningful significance level. The sample size of three vehicles per test lab was selected to allow calculation of a standard deviation, in turn used to calculate CV. Including a larger number of repeated tests would no doubt improve the findings of this study, but would be cost prohibitive.

Three different objective comparison methods were calculated in this study to evaluate the repeatability and reproducibility of the OMDB test procedure: CORA, ISO, and CVmod. Comparing the three methods based on the classification system presented in Table 5, the CVmod rating classifies more measurements as "good" than the CORA or ISO methods. Figure 8 shows a comparison of the three methods. In this scatterplot, each marker represents a single measurement, the X-axis represents the CORA score for that measurement, and the Y-axis represents either the CVmod score (orange asterisks) or the ISO score (blue circles). The furthest right box in the Figure 4 shows cases where CORA gives a "good" rating and ISO and CVmod gives "fair." The upper left

FIGURE 8 The ISO/CVmod scores relative to CORA scores for all time-histories evaluated

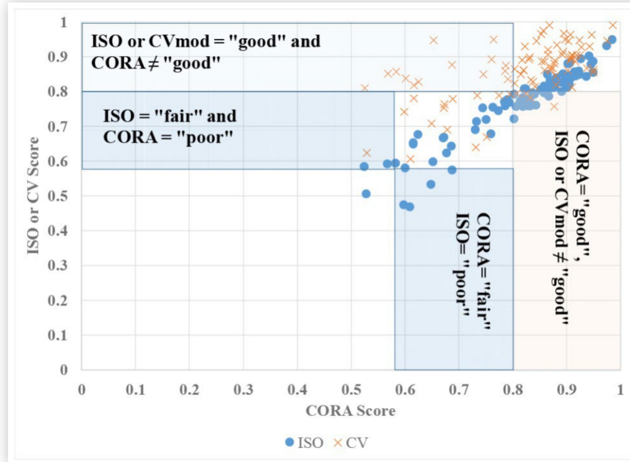


TABLE 20 Upper body rating prediction of each method

	CORA	ISO	CVmod
good	54%	44%	77%
fair	36%	38%	
poor	10%	18%	23%

box shows the opposite. CORA gives a "fair" or "poor" rating and ISO/CVmod gives a "good." The other two boxes are similar but are for "fair" instead of "good." For this dataset, there is a linear relationship between ISO and CORA (R2=0.90), which can be seen in Figure 8 since the blue circle markers closely follow the X=Y diagonal. The slope of this relationship is 0.87, indicating that the CORA rating is on average slightly higher than the ISO rating. No correlation between CVmod and CORA scores was found in this dataset, though there are more orange asterisk markers above the X=Y diagonal than below, suggesting that the CVmod rating is often higher than the CORA rating. Also, from this dataset there are no cases were ISO indicates "good" and CORA indicates "fair" or "poor."

Considering the rating classifications, the CVmod method indicates more "poor" ratings than the CORA or ISO methods, which could be a byproduct of the CVmod rating system including only two classifications, "good" and "poor." There were 21 measurements rated poor by the CVmod method, whereas only 4 measurements were rated "poor" by the CORA and 7 were rated "poor" by the ISO method. Therefore, if assuming that R&R must be better than "poor", the CVmod classification system would provide stricter guidelines for repeatability and reproducibility than CORA or ISO. However, if assuming that R&R must be "good", the CVmod classification system would be more lenient than the CORA or ISO methods.

Considering the upper body measurements, CVmod indicates a higher percentage of "good" measurements than CORA and ISO (Table 20). CVmod also indicates more "poor" measurements, which may result from the CVmod metric not including a "fair" classification. CORA indicates more "good" classifications than ISO, whereas ISO indicates more “fair” and “poor” than CORA.

The lower body measurements show a different trend than the upper body measurements (Table 21). CORA and CVmod indicated approximately the same number of “goods”, while ISO indicated the most “fair” ratings. CVmod is the only method to indicate “poor” rating for the lower body time-histories, which occurred in 8 out of the 47 lower body measurements.

When considering all of the available measurements, the three rating systems paint a consistent picture of within-lab repeatability (Figure 9). Based on CORA scores, results from all three labs were similar except for Lab3, which saw a higher percentage of “fair” ratings. Based on ISO scores, Lab2 received more “fair” ratings than Lab1, and Lab3 received more “poor” and “fair” ratings than Lab1 and Lab2. Based on CVmod, Lab3 received more “poor” ratings than Lab2, which in turn received more “poor” ratings than Lab1. This assessment suggests that the results from Lab1 are slightly more repeatable than those from Lab2 and Lab3, which may result from familiarity with the test procedure as Lab1 has conducted more tests of this type than the other two labs.

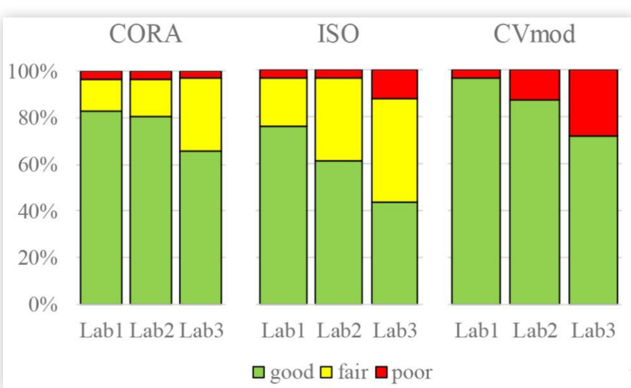
To put the occupant response repeatability and reproducibility findings into context, it is important to consider the relationship of the time-histories of the individual injury assessment metrics to their respective injury criteria. Injury criteria are often calculated using a combination of multiple time-histories, and usually focus on a single peak value. Therefore, considering CVs of injury criteria may be useful to determine whether fair or poor repeatability and reproducibility assessments are meaningful or in the noise. Thus, the injury criteria presented in Saunders et al. (2015) were considered for three cases: BrIC, Nij, and Multi-point Thoracic Injury Criterion.

BrIC. BrIC is calculated using the X-, Y-, and Z-axis angular velocity of the head. Both HeadAVx and HeadAVz

TABLE 21 Lower body rating prediction of each method

	CORA	ISO	CVmod
good	74%	45%	83%
fair	26%	55%	
poor	0%	0%	17%

FIGURE 9 Comparison of rating system assessment of repeatability within labs.



showed “poor” ratings in at least one comparison using both the CORA and ISO methods. BrIC was calculated for each of the tests and the resulting CV for all test labs was 7.7%, which would equate to a CVmod of 0.92 and a classification of “good.” Therefore, the poor reproducibility of the off-axis channels in this case does not negatively influence reproducibility with respect to the risk of brain injury.

Nij. Nij is calculated using the Z-axis force and the Y-axis moment, as measured at the upper neck load cell. Individually, the Z-axis force (NeckFz) showed “good” repeatability for all measurements and all methods, while the Y-axis moment (NeckMy) was “fair” for all comparisons using the CORA and ISO methods and “poor” for the Lab3 comparison using the CVmod. Calculating Nij for all test labs results in a CV of 9.2%, which would equate to a CVmod of 0.91 and a classification of “good.” Therefore, the fair to poor reproducibility of the neck Y-axis moment channels does not negatively influence reproducibility with respect to the risk of neck injury.

Multi-point Thoracic Injury Criterion. Chest injury risk is calculated using the maximum peak resultant deflection of any of the four quadrants of the chest. The location of peak deflection typically occurs in the quadrant closest to the location of the belt across the chest, which for the driver is either the upper right or lower right quadrant. For the nine tests in this study, the location of peak deflection reproducibly occurred in the upper right chest, and the upper right chest deflection (ChestRU) demonstrated a good repeatability and reproducibility classification for all three rating methods. Measurement locations further away from the belt were lower in magnitude, and perhaps consequently less reproducible due to the lower signal-to-noise ratio. The lower left chest deflection (ChestLL), which was categorized as fair using CORA and poor using ISO and CVmod, is the furthest from the belt and saw on average less than half of the peak resultant deflection of the ChestRU measurement location. Therefore, the reproducibility of the deflection in quadrants other than ChestRU is not expected to influence reproducibility with respect to chest injury risk.

There are many parameters that may affect the response of the tibia. Three parameters may be significant for the oblique test condition. The first is the location of the knee relative to the dash. The knee position affects where and when the instrument panel contact occurs. The second parameter is the placement of the feet. The placement of the feet affects the loading of the ankle and can cause the tibia to interact differently with the instrument panel. The third is interior intrusion. The rate of intrusion and magnitude affects the timing and severity of the tibia loading.

There was pattern to the placement of the lower legs among the test facilities. Figure 10 and Figure 11 show the XZ and XY position of the right ankle. The right ankle placement was different for each facility. Lab1 had the more consistent placement of the right ankle. Lab2_1 and Lab2_3 had similar placement of the right ankle as Lab1. Lab2_2 right ankle was positioned forward of Lab2_1 and Lab2_3 by 28 mm and 14 mm outboard. Lab3_2 and Lab3_3 placed the right ankle rearward of Lab1 and Lab2 . Lab3 placed the right ankle further inboard. The ankle placement affects the knee location. The right knee had difference in the y direction of 41 mm.

FIGURE 10 XZ position of the right ankle

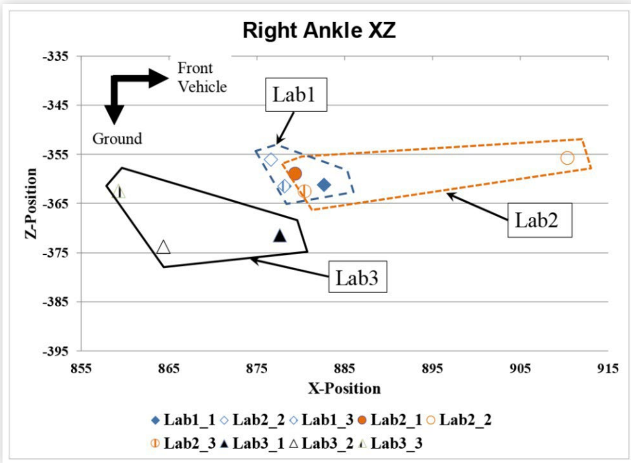
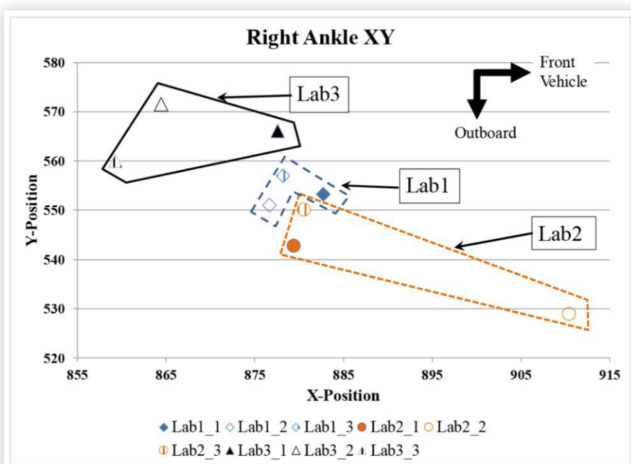


FIGURE 11 XY position of the right ankle



Comparison to Full Frontal Test Procedure

Saunders and Parent [11] compared a series of three repeat tests of the Chevrolet Cruze following NHTSA's oblique test procedure to paired vehicle tests in other frontal crash test procedures. Since some of the paired vehicle tests following the other established test procedures only included two vehicles, the CVs were not calculated as these would not be particularly meaningful with only two data points. Instead, Saunders and Parent [11] compared the average difference between the responses of each paired vehicle response. This analysis showed that the oblique procedure produced similar responses as the other test procedures. The following analysis investigates the correlation between the time-histories (CORA rating) of the 56 kph full frontal rigid barrier (FRB) test procedure compared to the oblique test procedure.

NHTSA's public vehicle database was searched for paired vehicles tested in the FRB test procedure. The paired vehicles have a Hybrid III 50th percentile male ATD in the driver seat. The paired vehicles were the same make, model, year, transmission, and engine. A limitation of this comparison is that these paired vehicles were not tested in a controlled R&R study, thus there may be some differences in the exact test implementation. However, these differences are expected to be within the tolerances of the ATD qualification procedure and FRB test procedure. One known difference was that the model year 2010 vehicles included in this comparison used different right front passenger ATDs, which would not be expected to influence the response of the driver. Other paired tests included rear seat occupants; to ensure that the driver's response was not influenced by the rear seat occupant, test video was reviewed to insure the no seatback contact occurred. This search found eight paired vehicles (Appendix A).

Figure 12 through Figure 14 show the CORA scores for the vehicle, driver ATD's upper body, and driver ATD's lower body response, respectively. Each figure shows the average and standard deviation for each channel being evaluated for the FRB. CORA scores for occupant response evaluations were

FIGURE 12 Vehicle response CORA scores for the FRB and OMDB test procedure

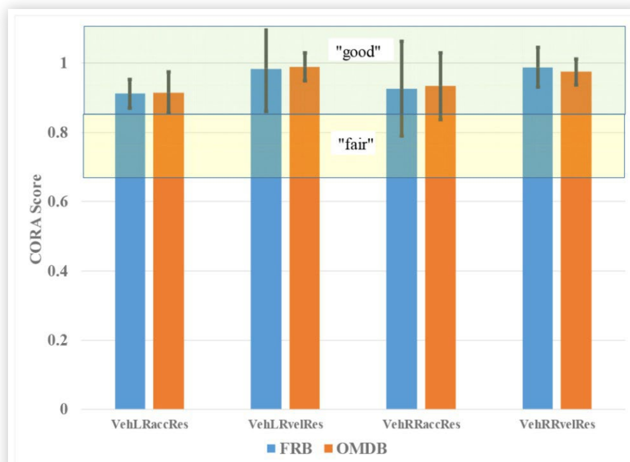


FIGURE 13 Driver ATD's upper body CORA scores for the FRB and OMDB test procedure

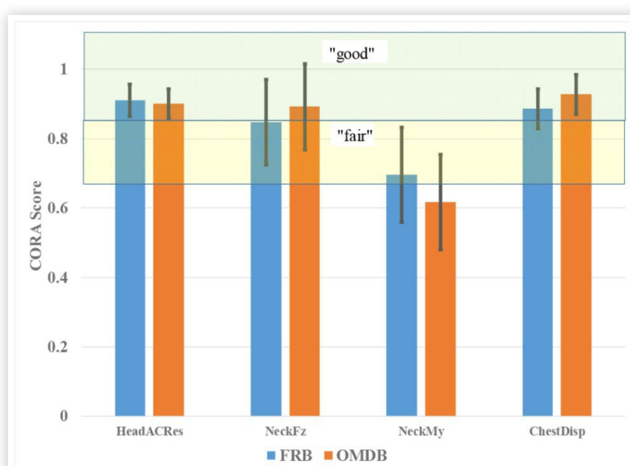
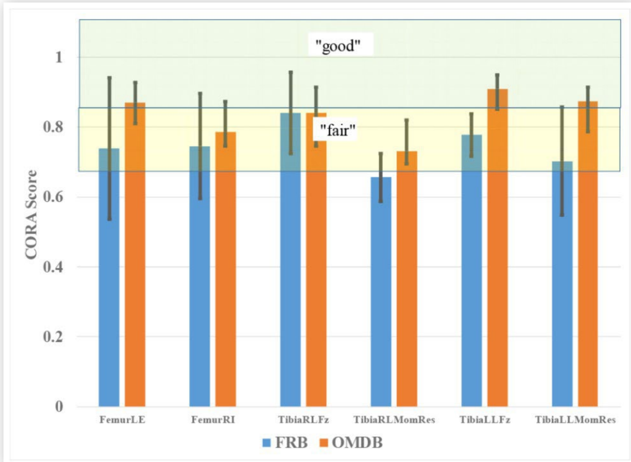


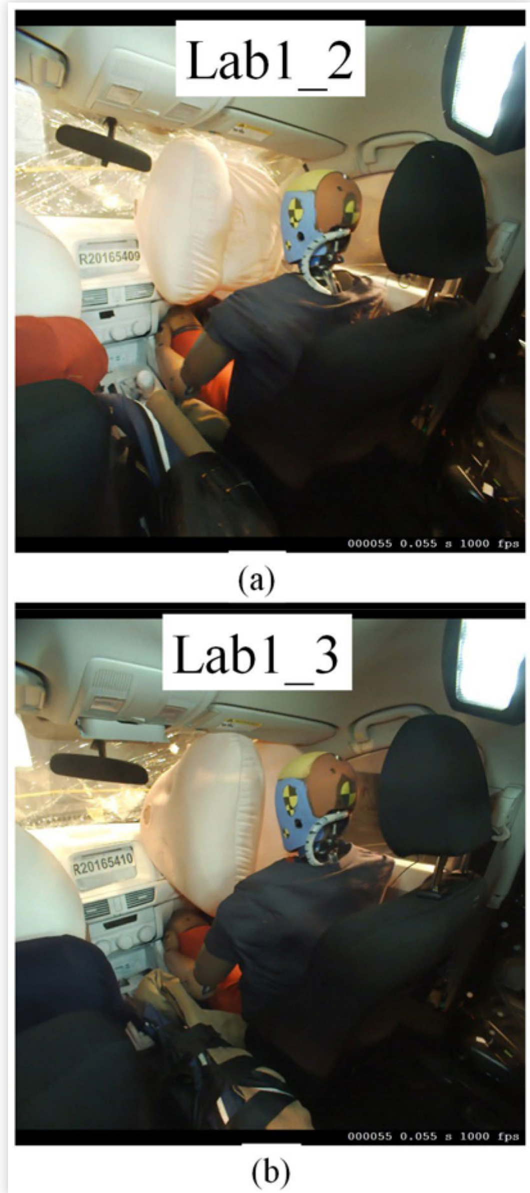
FIGURE 14 Driver ATD's lower body CORA scores for the FRB and OMDB test procedure



compared only for measurements available to both the THOR and Hybrid III ATDs. In the case of chest deflection, CORA scores for the single chest deflection measurement of the Hybrid III were compared to the ChestRU measurement of the THOR, as this was the quadrant of peak chest deflection. The LabAll dataset was used to calculate the average and standard deviation for the 36 time histories comparison. For the vehicle 3 out of the 4 comparisons had a higher CORA score than the FRB (Figure 12). The upper body responses from the OMDB test are similar to those of the FRB test (Figure 13). Average CORA scores were higher for the OMDB procedure for the NeckFz and Chest Disp comparisons, similar for HeadACres, and lower for NeckMy. However, as noted earlier, variation in NeckMy in the OMDB tests did not negatively influence reproducibility in the injury criteria calculation. All the OMDB test lower body average CORA scores were greater than the corresponding CORA scores for the FRB test (Figure 14). It can be seen that some of the measurements for the FRB test procedure were rated "fair" and one was rated "poor." Furthermore, the standard deviations from the OMDB and FRB test procedures overlap for all measurements except for TibiaLLMomRes, where the CORA scores demonstrate better reproducibility for the OMDB procedure.

During this test series, several of the 2016 CX-5 vehicles experienced significant breakage of the windshield glazing resulting in fabric tears in the passenger airbags. These sporadic tears caused loss of pressure in the airbag, which may have contributed to variations in the right passenger kinematics and injury measures. In the tests at Lab1 the right front passenger airbag did not function as intended. The airbag experienced tearing during its inflation, which caused the airbag to perform differently between tests. This can be seen by capturing a still photo from the video of the passenger for Lab1_2 and Lab1_3 at 55 ms from impact (Figure 15 (a) and (b), respectively). The two chambers in the airbag in Lab1_3 seem to be inflated more than the two chambers in Lab1_2, as evidenced by the gap in windshield coverage and loose airbag fabric in the top right corner of Figure 15 (a). The manufacturer developed a possible solution to prevent the tears before the next lab performed their tests. Unfortunately, the

FIGURE 15 Right front passenger state for test Lab1_2 and Lab1_3 at 55 ms after impact



solution did not work and there were also tears in the airbags for Lab2. As a result, the manufacturer developed a different solution before the tests were performed at Lab3. The passenger airbags for Lab3 only had slight tears. Due to the variations in passenger airbag integrity in these tests, the authors decided to not assess the repeatability and reproducibility of the passenger ATD as part of this study.

Summary

NHTSA has conducted a repeatability and reproducibility assessment for the OMDB test procedure. Nine Mazda CX-5 vehicles were tested 3 times at 3 different crash test facilities. The test results from all 9 tests were compared to examine the performance of the OMDB, target vehicle, and ATD performance measures.

Three different rating systems were evaluated: CORA, ISO, and CVmod. For this dataset a linear relationship between CORA and ISO scores was found. The CVmod indicates more "poor" rating than CORA and ISO methods, which may result from the higher "poor" threshold for CVmod compared to the corresponding threshold for CORA and ISO.

When considering occupant response measurements as the main factor in determining R&R, the driver responses were generally rated "good" or "fair". While there were several occupant response parameters classified as having "poor" repeatability and/or reproducibility, these parameters were either off-axis or of low magnitude relative to the injury criteria they are used to calculate, and thus did not negatively influence reproducibility of injury risk. Also, when comparing the OMDB test procedure to the FRB test procedure the OMDB test procedure the ATD and vehicle parameters were rated the same or higher for this vehicle.

The difference in the rating of the lower leg parameters for each lab and between all labs was investigated by looking at the placement of the leg and foot. Examination of the test reports showed some variation in the ankle and knee placement between repeat tests and between test facilities. This dummy positioning difference could account for some of the variation in leg performance measures.

Based on the repeatability and reproducibility metrics utilized in this study, this test series demonstrated generally repeatable and reproducible results for the OMDB responses, test vehicle responses, and some of the driver ATD responses. However, the front passenger ATD responses were not analyzed due to front passenger airbag performance limitations. The results have also identified a few areas where the test procedure can be refined, including improved vehicle sensor mounting requirements and dummy seating procedure.

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Appendix A

TABLE 22 56 kph full frontal rigid barrier tests

TSTNO	MAKED	MODELD	YEAR	BODY
6258	CADILLAC	CTS	2008	4S
6271	CADILLAC	CTS	2008	4S
4244	CHEVROLET	TRAILBLAZER	2002	UV
5036	CHEVROLET	TRAILBLAZER	2002	UV
5061	DODGE	RAM	2002	PU
4240	DODGE	RAM1500	2002	EX
6724	HONDA	INSIGHT	2010	5H
6729	HONDA	INSIGHT	2010	5H
6759	HYUNDAI	GENESIS	2010	2C
6764	HYUNDAI	GENESIS	2010	2C
6736	KIA	FORTE	2010	4S
6766	KIA	FORTE	2010	4S
6642	LEXUS	RX350	2010	UV
6643	LEXUS	RX350	2010	UV
3915	TOYOTA	TUNDRA	2002	EX
5073	TOYOTA	TUNDRA	2002	4P

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